

# The Pulsed Spectra of Two Extraordinary Pulsars

Mallory Roberts<sup>\*†</sup>, Scott Ransom<sup>\*†</sup>, Fotis Gavriil<sup>\*</sup>, Vicky Kaspi<sup>\*</sup>, Pete Woods<sup>\*\*‡</sup>,  
Alaa Ibrahim<sup>§¶</sup>, Craig Markwardt<sup>§</sup> and Jean Swank<sup>§</sup>

<sup>\*</sup>*Dept. of Physics, McGill University, 3600 University St. Montréal, QC. H3A 2T8, Canada*

<sup>†</sup>*Dept. of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA. 02139*

<sup>\*\*</sup>*Universities Space Research Association*

<sup>‡</sup>*National Space Science and Technology Center, 320 Sparkman Drive, Huntsville, AL 35805*

<sup>§</sup>*NASA Goddard Space Flight Center, Greenbelt, MD 20771*

<sup>¶</sup>*Department of Physics, George Washington University, Washington, DC 20006*

## Abstract.

We report on X-ray monitoring of two isolated pulsars within the same RXTE field of view. PSR J1811–1925 in the young supernova remnant G11.2–0.3 has a nearly sinusoidal pulse profile with a hard pulsed spectrum (photon index  $\Gamma \sim 1.2$ ). The pulsar is a highly efficient ( $\sim 1\%$  of spin-down energy) emitter of 2–50 keV pulsed X-rays despite having a fairly typical  $B \sim 2 \times 10^{12}$  G magnetic field. PSR J1809–1943/XTE J1810–197 is a newly discovered slow ( $P = 5.54$  s), apparently isolated X-ray pulsar which increased in flux by a factor of 100 in 2003 January. Nine months of monitoring observations have shown a decrease in pulsed flux of  $\sim 30\%$  without a significant change in its apparently thermal spectrum ( $kT \sim 0.7$  keV) or pulse profile. During this time, the spin-down torque has fluctuated by a factor of  $\sim 2$ . Both the torque and the flux have remained steady for the last 3 months, at levels consistent with a magnetar interpretation.

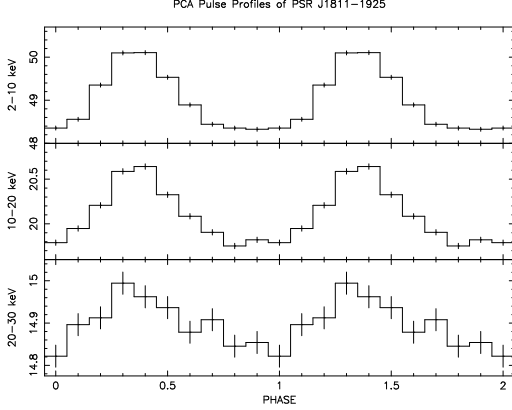
## INTRODUCTION TO THE G11.2–0.3 FIELD

The region near the supernova remnant G11.2–0.3 is incredibly rich. Within a  $\sim 1 \text{ deg}^2$  are at least 5 supernova remnants [1] and several young pulsars.  $\sim 1.2^\circ$  away is the Soft Gamma-Ray Repeater SGR 1806–20 and not much further away is the possible SGR 1801–23. However, this region does not appear to be along a tangent line of a spiral arm or especially abundant in star forming regions for an inner region of the Galactic plane. The region is within the area covered by the RXTE Galactic bulge monitoring program [2]. This in combination with the facts that SNR G11.2–0.3 is one of only 6–8 remnants associated with historical events [3] and SGR 1806–20 is one of only 4 confirmed SGRs has caused this small region to be unusually well observed. Even so, it is quite surprising that not only does the pulsar in SNR G11.2–0.3 have unusual X-ray properties, but that while monitoring it with RXTE a transient Anomalous X-ray Pulsar appeared within the PCA field of view. Here we report on the pulsed spectra of these two extraordinary pulsars.

## PSR J1811–1925, THE PULSAR IN SNR G11.2–0.3

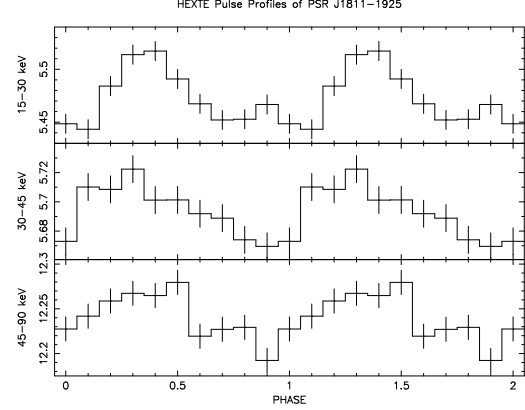
SNR G11.2–0.3 is remarkable in several ways. It has a circular shell which is bright in both radio and X-rays with a central pulsar wind nebula [see 4, 5, for details of the nebular emission]. Measurements of the expansion of the radio shell have established its age to be  $\tau \sim 2,000$  yr [6], which is consistent with being born in the historical event of 386 A.D. The PWN is powered by one of the brightest X-ray emitting pulsars, PSR J1811–1925, whose characteristic age is  $\tau_c \sim 24,000$  yr [7]. The discrepancy with the true age of the SNR implies it was born spinning near its current spin period  $P \sim 65$  ms [8]. The pulsar's X-ray spectrum is very hard ( $\Gamma \sim 1$ ) and has broad, nearly sinusoidal pulse profile reminiscent of the profiles of PSR B1509–58 [9] and the pulsar in the distant young remnant Kes75 [10], which are also very young spin-powered pulsars with very high hard X-ray efficiencies.

We have been monitoring PSR J1811–1925 with RXTE on a monthly basis since March 2002, with the hope of constraining the pulsar braking index to strengthen the case for a slow initial period. The timing properties will be reported elsewhere. Here, we present the pulse profile from the combined data set as a function of energy which is seen in both the PCA and HEXTE



**FIGURE 1.** RXTE PCA pulse profiles of PSR J1811–1925

data (Fig. 1, 2), and measurements of the hard X-ray pulsed spectrum. The pulsed emission is very hard, the spectrum being well fit in the 2.5–30 keV band by a single power law with a photon index of  $\Gamma = 1.16$  (0.97 – 1.36, 90% confidence) with no sign of a cutoff in either the PCA or HEXTE data. The pulsations are clearly seen above 45 keV in the HEXTE data, remaining nearly sinusoidal. At the best determined distance of 5 kpc, assuming beaming into  $\pi$  steradians implies a remarkable  $\sim 1\%$  of the spin-down power is being emitted as pulsed 1–50 keV X-rays. The pulsed properties of PSR J1811–1925 are very similar to those of the young ( $\tau \sim 1700$  yr) 150 ms pulsar PSR B1509–58 [9]. Both have broad profiles with no apparent dependence on energy, similar spectra up to 50 keV, and similar X-ray efficiencies. The spectrum of PSR B1509–58 shows curvature which becomes apparent only above 50 keV [11], steepening to a power law of  $\Gamma \sim 1.7$  before cutting off at  $\sim 10$  MeV. The high X-ray efficiency of PSR J1811–1925 requires its emission to have curvature, a spectral break or cut-off below a few MeV, similar to PSR B1509–58 and leaves little power for GeV emission. However, unlike PSR B1509–58 which has  $B \sim 1.5 \times 10^{13}$  G and about three times the spin-down energy, or PSR J1846–0248 in Kes 75 which has an even higher magnetic field, PSR J1811–1925 has a typical magnetic field of  $\sim 2 \times 10^{12}$  G. This suggests that unusually efficient magnetospheric pulsed X-ray emission results from a special geometry and not from a high magnetic field or spin-down energy, which may have important implications for models of magnetospheric emission. Note as well that while PSR B1509–58 is a radio pulsar, neither PSR J1811–1925 or PSR J1846–0248 have yet been seen in radio despite targeted searches [12].

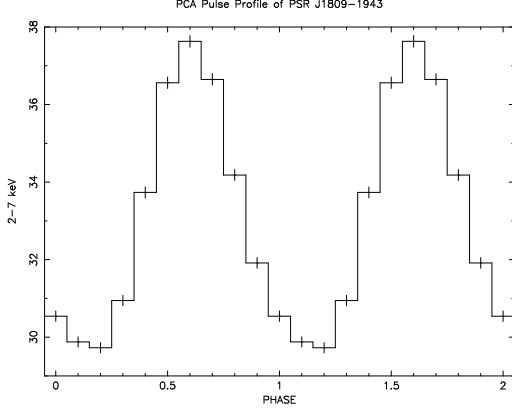


**FIGURE 2.** RXTE HEXTE pulse profiles of PSR J1811–1925

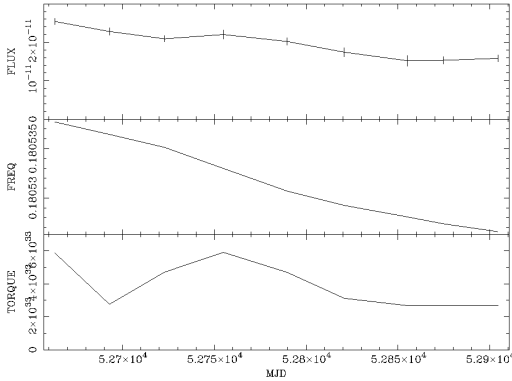
### A NEW AXP? XTE J1810–197 / PSR J1809–1943

In July 2003, a TOO observation of the soft  $\gamma$ -ray repeater SGR 1806–20 revealed the previously undetected 5.54 s X-ray pulsar XTE J1810–197/ PSR J1809–1943 [13] with a sinusoidal profile (Fig.3). Analysis of our G11.2–0.3 monitoring data showed the new pulsar first became detectable by RXTE in Jan. 2003. In combination with data from the PCA monitoring program of the Galactic bulge region [2], a phase connected timing solution has been obtained which shows large torque variations but an overall spin-down consistent with the new source being an anomalous X-ray pulsar [14]. Subsequent observations with Chandra and XMM-Newton localized the source and measured its soft spectrum, which is best fit by a two component blackbody ( $kT \sim 0.3$  keV and  $kT \sim 0.7$  keV). Archival ROSAT and ASCA observations detected the source at a flux level about a factor of 100 less than the outburst flux, with a temperature similar to the lower blackbody temperature observed by XMM-Newton [15].

In Fig.4 we present the pulsed flux history of the transient X-ray pulsar PSR J1809–1943 as observed in the G11.2–0.3 monitoring data covering the period from Jan. 2003 to Sep. 2003. All of the PCA observations are well fit by a single blackbody with  $kT = 0.7$  keV in the 2.5–8 keV range. There is no evidence for a change in the spectrum other than a drop of about 30% in the overall flux. During this time, there were spin-down torque fluctuations of more than a factor of 2. For the last three observations, spanning about 90 days, both the flux and the torque have remained essentially constant. If the current torque is approximately that of dipole braking, then the implied surface magnetic field is  $B \sim 3 \times 10^{14}$  G, on the low end of claimed magnetars. The absorption column towards the source is only  $nH \sim 0.6 \times 10^{21} \text{ cm}^{-2}$ ,



**FIGURE 3.** RXTE PCA 2-7 keV pulse profile of PSR J1809-1943



**FIGURE 4.** TOP: Flux history (in  $\text{erg cm}^{-2}\text{s}^{-1}$ ) of PSR J1809-1943. MIDDLE: Frequency (in  $\text{s}^{-1}$ ) evolution of PSR J1809-1943. BOTTOM: Spin-down torque (in  $\text{erg s}^{-1}$ ) evolution of PSR J1809-1943.

about one third that of G11.2-0.3, suggesting it might be significantly closer than the latter's distance of 5 kpc. This also makes this source a good target for infrared studies. Even at a distance of only 1 kpc, the X-ray luminosity is  $\sim 5 \times 10^{34} \text{erg}^{-1}$ , significantly larger than the spin-down torque. Thus, it meets the basic criteria for being an Anomalous X-ray pulsar.

## ACKNOWLEDGMENTS

This research was partially supported by NSERC Discovery and Steacie grants, the Canada Research Chairs, NATEQ, CIAR and NASA.

## REFERENCES

1. Brogan, C. L., Devine, K. E., Lazio, T. J., Kassim, N. E.,

- Tam, C. R., Briskin, W. F., Dyer, K. K., and Roberts, M. S. E., *ArXiv Astrophysics e-prints* (2003).
2. Swank, J., and Markwardt, C., "Populations of Transient Galactic Bulge X-ray Sources," in *ASP Conf. Ser. 251: New Century of X-ray Astronomy*, 2001, pp. 94-+.
3. Clark, D. H., and Stephenson, F. R., *The Historical Supernovae*, Pergamon, Oxford, 1977.
4. Roberts, M. S. E., Tam, C. R., Kaspi, V. M., Lyutikov, M., Vasisht, G., Pivovarov, M., Gotthelf, E. V., and Kawai, N., *ApJ*, **588**, 992-1002 (2003).
5. Tam, C., Roberts, M. S. E., and Kaspi, V. M., *ApJ*, **572**, 202-208 (2002).
6. Tam, C., and Roberts, M. S. E., *ApJ*, **598**, L27-L30 (2003).
7. Torii, K., Tsunemi, H., Dotani, T., Mitsuda, K., Kawai, N., Kinugasa, K., Saito, Y., and Shibata, S., *ApJ*, **523**, L69-L72 (1999).
8. Kaspi, V. M., Roberts, M. S. E., Vasisht, G., Gotthelf, E. V., Pivovarov, M., and Kawai, N., *ApJ*, **560**, 371-377 (2001).
9. Rots, A. H., Jahoda, K., Macomb, D. J., Kawai, N., Saito, Y., Kaspi, V. M., Lyne, A. G., Manchester, R. N., Backer, D. C., Somers, A. L., Marsden, D., and Rothschild, R. E., *ApJ*, **501**, 749-757 (1998).
10. Gotthelf, E. V., Vasisht, G., Boylan-Kolchin, M., and Torii, K., *ApJ*, **542**, L37-L40 (2000).
11. Cusumano, G., Mineo, T., Massaro, E., Nicastro, L., Trussoni, E., Massaglia, S., Hermsen, W., and Kuiper, L., *A&A*, **375**, 397-404 (2001).
12. Crawford, F., Kaspi, V. M., Manchester, R. N., Lyne, A. G., Camilo, F., and D'Amico, N., *ApJ*, **553**, 367-374 (2001).
13. Markwardt, C. B., Ibrahim, A. I., and Swank, J. H., "XTE J1810-197," in *International Astronomical Union Circular*, 2003, pp. 2-+.
14. Ibrahim, A. I., Markwardt, C., Swank, J., Ransom, S., Roberts, M., Kaspi, V., Woods, P., Safi-Harb, S., Balman, S., Parke, W., Kouveliotou, C., Hurley, K., and Cline, T., *ArXiv Astrophysics e-prints* (2003).
15. Gotthelf, E. V., Halpern, J. P., Buxton, M., and Bailyn, C., *ArXiv Astrophysics e-prints* (2003).